Model for energy efficiency in radio over fiber distributed indoor antenna Wi-Fi network

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***Abstract*—Distributed antenna systems (DAS) are known to improve coverage and performance of wireless communications in indoor environments. In this paper, the power consumption and energy efficiency of a DAS using radio over fiber (RoF) are evaluated and compared with those in a centralized antenna system. The instantaneous power consumption curves of a Wi-Fi access point and dongle combination are physically measured for different transmission configurations, yielding a distance-dependent energy efficiency model. In a second step, computer simulations show that a distributed system with four antennas is 3.8 times more energy-efficient than a centralized antenna system, while the total radiated power is divided by a factor of two.**

I. Introduction

The issue of power consumption and energy efficiency of indoor wireless networks and more generally energy management in telecommunication is a crucial one. There are currently new contexts for power saving, not only in terminals to increase battery life, but also in access points to reduce the carbon footprint (towards "greener" telecoms).

Furthermore, demands on throughput and performance keep increasing, especially in indoor environments where users are densely located. The advantages of RoF distributed antenna systems are very low fiber transmission loss, large bandwidth, and low transmit power levels, which enable us to improve the coverage of in-building wireless services [1].

In this paper, our aim is to study the energy efficiency issue within RoF distributed antenna systems and to compare it with a centralized antenna system.

In the first part, a propagation model in a dense indoor environment is presented, to compare the maximum data rate given by the 802.11 standard in a centralized antenna system with a DAS scheme. We then study the influence of the modulation scheme from a set of measurements of the actual power consumption at the access point and terminals during a data transmission. Furthermore, modelling and simulation of the overall energy consumption in an RoF distributed antenna network are presented.

II. Maximum data rate study

A. Indoor propagation model

Although indoor radiofrequency (RF) propagation was extensively studied in the past, the received RF power cannot be accurately predicted. Multiple scattering and reflections from walls and furniture, as well as shadowing effects, cause strong time and space variations in received power.

The model used is statistical and does not require any graphical database. Indeed our goal is not to find quantitative results, but to evaluate possible energy consumption discrepencies between the centralized antenna and DAS schemes. Therefore, we shall use a simple model to estimate the RF power received by the receiver as a function of distance.

The average received power can be expressed (in dBm) as :

$$P_r = P_t + G_t + G_r - PL \tag{1}$$

where P_t is the transmit power in dBm, G_t and G_r are the transmitter and receiver antenna gains, respectively, and PL is the path loss in dB. Considering isotropic antennas, $G_t = G_r = 0$ dBi and the path loss is given by the following equation [2] :

$$PL = PL(d_0) + 10n \log_{10} \frac{d}{d_0} \tag{2}$$

where $PL(d_0)$ is the path loss at $d_0 = 1$ m, $PL(d_0) = -20 \log_{10}(c/4\pi f d_0) = 40.2$ dB at 2.4 GHz, d is the distance between transmitter and receiver and n is the power decay index.

Considering a dense environment with small rooms, typically a multifloor office where each employee has his/her own office, the power decay index is between 4 and 6 [2]. In our simulations, we shall use $n = 5.12$ [3].

B. Relationship between received power level and data rate

Regarding the Wi-Fi standard, the modulation scheme is adjusted according to the received power level. When a modulation is selected, the maximum reachable datarate is set by the 802.11 standard. Datasheets of Wi-Fi access points or Wi-Fi cards provide the relationship between the modulation used and the receiver sensitivity. As an example, these data are presented in Table I for a Netgear Access Point [4].

C. Simulation setup

Combining the receiver sensitivity from datasheets and the indoor propagation model, we can compute a map of the highest reachable throughput as a function of the distance. The size of the area under consideration is 40 m × 40 m.

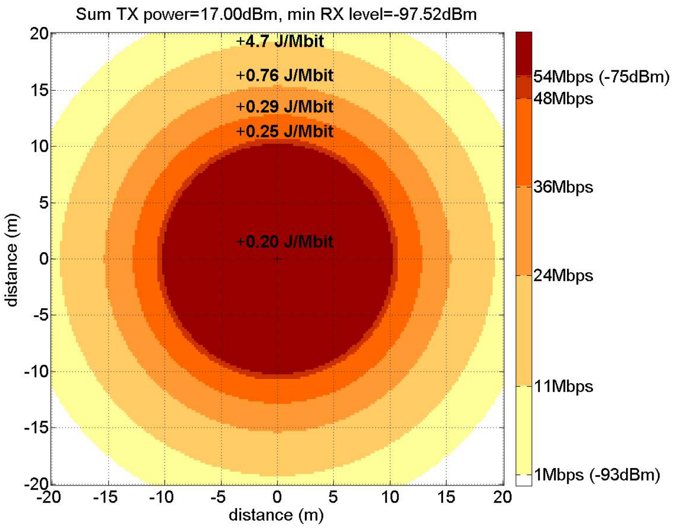

Fig. 1: Map of the highest 802.11 reachable data rate with one access point, considering a radiated power of 17dBm

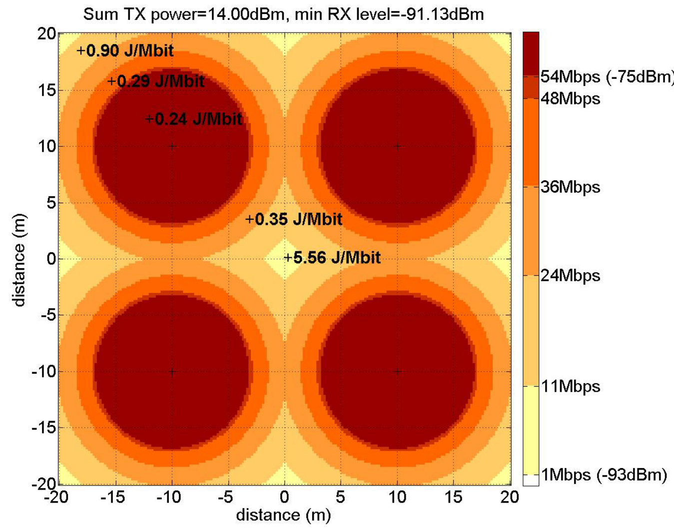

Fig. 2: Map of maximum 802.11 data rate with four access points delivering a total power radiation of 14 dBm (8dBm per distributed antenna)

TABLE I: Maximum Data rate given by the 802.11 standard relative to the power received by the terminal (box/dongle) [4]

Standard	Data rate	Receiver sensitivity
802.11b	1 Mbps	-93 dBm
802.11b	11 Mbps	-89 dBm
802.11g	24 Mbps	-84 dBm
802.11g	36 Mbps	-80 dBm
802.11g	48 Mbps	-76 dBm
802.11g	54 Mbps	-75 dBm

In addition to this, we do not restrict the study to a planar topology, as several floors may exist between a terminal and an access point.

Figure 1 presents the evolution of the reachable throughput as a function of the distance between the access point and the mobile terminal, with a radiated power of 17 dBm. The maximum data rate given by the 802.11 standard is reached when the distance between the terminal and the access point is less than 10.2 m (i.e. 20.5% of the total area). However, when the distance is greater than 23 m, no connection is possible (i.e 7.7% of the total area).

In a second step, the same area is considered with four distributed antennas with half the overall radiated power (i.e. each distributed antenna emits 8 dBm of power). The simulation result is presented in Figure 2, showing better coverage, despite a lower total radiated power. Indeed, a terminal can communicate with an access point in the whole area. Moreover, the maximum datarate is reachable over 584 m^2, representing 36.5% of the total area.

These simulations show the advantages of a distributed antenna network in terms of coverage and radiofrequency exposure. In the following section, the energy efficiency of an 802.11 network is studied.

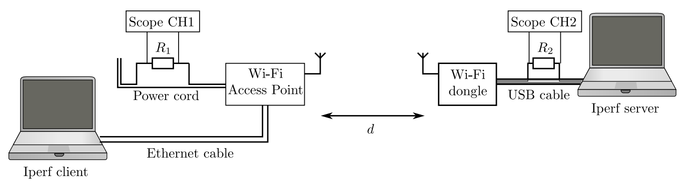

Fig. 3: Power measurement setup

III. Measuring energy efficiency in an 802.11 network

In the literature, there are few measurement reports dealing with the energy consumption of access points and terminals during a transmission when the modulation type changes. In general, device specifications showing drive current curves while transmitting and receiving are not sufficient to calculate energy consumption accurately.

A. Experimental setup

Power measurements were performed using a Netgear WG 602 Access point in the infrastructure mode (no encryption) and a Wi-Fi USB dongle TL-WN422g from TP-Link. Other types of access points or USB dongles have been used with similar results.

The configuration of the access point enables us to choose the standard (b/g) and the modulation associated with the maximal reachable datarate presented in the previous section. Other parameters can be freely choosen, such as fragmentation length (2346 Bytes) or RTS Threshold (2347 Bytes).

A TCP connection between an access point and a USB dongle was implemented using the Iperf software [5], as shown in Figure 3. This software enables us to record the effective throughput, sometimes referred to as "goodput".

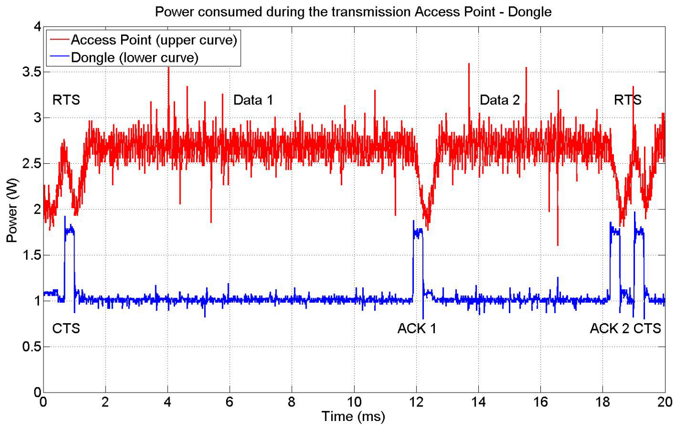

Fig. 4: Instantaneous power consumed during the transmission from a Netgear access point to a TP Link dongle using 1Mbit/s 802.11b. The RTS Threshold and Fragmentation length contain 2346 and 1024 bytes, respectively.

Laptop computers (Windows XP) were used and configured to maximize the resources allocated to the present task.

B. Electrical power measurement setup

The power measurement setup is depicted in Figure 3. The measurement scheme is designed to measure and record the instantaneous and average power consumptions of the access point and the USB Wi-Fi dongle during the transmission stage. In order to measure instantaneous power, we monitored the supply current of the access point and the dongle.

The power required by the access point/dongle is the product of the voltage drop and the current across the access point/dongle. The current was measured by placing a calibrated resistor in line with the power cord. The voltage drop across accurate resistors ($R_1 = 0.102\ \Omega$ and $R_2 = 0.097\ \Omega$) was then observed and captured using a digitizing oscilloscope (Picoscope 2205 from Pico Technology).

To ensure an operating voltage of 9 V for the Netgear WG 602 access point, the power cord was connected to a regulated power supply. The operating voltage of the USB dongle (5 V) was provided by the laptop computer and controlled during the transmission with the picoscope. To avoid inherent ground problems, the two laptop computers were operated in battery mode.

The resulting supply current curves are presented in Figure 4 for the 802.11b standard, and a modulation enables a maximum data rate of 1Mbit/s. The RTS Threshold was 1024 bytes to make it possible to visualize RTS and CTS signals. Two main levels can be noticed on both the access point and dongle curves: a high level corresponding to the transmission (2.75 W for the access point and 1.75 W for the dongle) and a low level corresponding to the receive mode or idle mode (1.88 W for the access point and 1.04 W for the dongle).

It can be noted that the power supply current is smoothed at the transition edges at the access point. Therefore, when the data rate increases we cannot distinguish the different levels anymore.

TABLE II: Mean power consumption and energy per bit goodput for different 802.11 standard during a transmission between the access Point (Netgear WG602) and the dongle (TL-WN422g)

Standard	D (Mbit/s)	P_{AP} (W)	P_{dgl} (W)	EBG (J/Mbit)
b (1Mbps)	0.80	2.71	1.06	4.7
b (11Mbps)	4.8	2.47	1.18	0.76
g (24Mbps)	12.7	2.48	1.24	0.29
g (36Mbps)	14.8	2.42	1.24	0.25
g (48Mbps)	17.5	2.38	1.25	0.21
g (54Mbps)	18	2.36	1.25	0.2

Table II presents the power consumption during a transmission between the access point and the dongle when the modulation changes, for a fragmentation length of 2346 Bytes and an RTS Threshold of 2347 Bytes. The distance between the dongle and the access point was $d = 1.5$ m. The mean goodput is measured using Iperf software.

Different behaviors can be distinguished, depending on the modulation scheme. For the 802.11b modulation, the mean power consumed by the access point is higher than for the best modulations owing to the reduction in packet transmission time. For the same reason, the power consumed by the dongle increases with the data rate. Indeed, the dongle sends acknowledgments and CTS signals more frequently. Moreover, the goodput measured by Iperf is lower than the maximum data rate given by the 802.11 standard.

C. Energy efficiency metric

In order to evaluate the actual energy efficiency of the Wi-Fi transmission, an appropriate metric is required to take into account the power consumption at the access point and dongle, as well as the effective throughput or goodput. For that purpose, we define the "energy-per-bit goodput" (EBG) as follows :

$$\text{EBG (J/Mbit)} = \frac{P_{AP} + P_{dgl}\ \text{(W)}}{D\ \text{(Mbit/s)}} \tag{3}$$

where P_{AP} and P_{dgl} are the mean power consumed by the access point and the dongle respectively during a transmission, and D is the mean goodput measured by Iperf. The EBG parameter tells us how much energy the system has to spend to transmit one bit of payload data [6].

EBG results are shown in Figure 1 and in the last column of Table II. The EBG value is 23.5 times higher for 802.11b (1 Mbps) than for 802.11g (54 Mbps), due to both the reduction in the overall power consumed and the increase in goodput.

When the distance between the access point and the mobile terminal increases (Figure 1), the EBG increases. To improve energy efficiency, the distance between the terminal and the access point has to be less than about ten meters for a radiated power of 17 dBm. We shall therefore study in the next section the energy efficiency of a distributed antenna network by RoF,

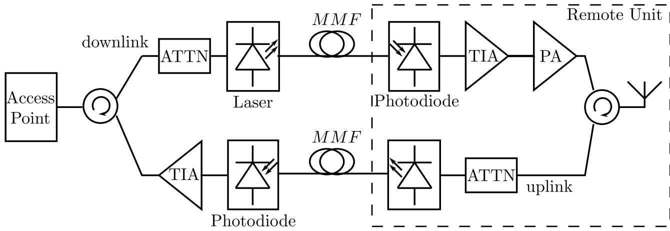

Fig. 5: Generic layout of bi-directional radio-over-fiber link

TABLE III: RoF link parameters [7]

Parameter	Power consumption
Laser (VCSEL)	22 mW
Photodiode	10 mW
Laser drive amplifier (ATTN)	22 mW
Transimpedance amplifier (TIA)	22 mW
Power amplifier (PA)	22 mW

with the goal of reducing the distance between the distributed antennas and the terminals.

IV. Energy efficiency of a distributed antenna system

A. Architecture

Figure 5 presents the architecture of a radio-over-fiber DAS link. The signals from the access point are split electrically to achieve several remote units. RF signals are adapted (ATTN) to a suitable level to directly modulate a laser diode. The resulting intensity-modulated optical carrier is transported over multimode optical fiber to a photodiode and transimpedance amplifier (TIA) to perform opto-electrical conversion. The RF signal obtained is transmitted wirelessly after a power amplifier (PA) stage. For the uplink communication, the same components are used in a symmetrical manner.

In an architecture where four antennas are distributed, RF passive splitters and combiners can be used. As the loss introduced by these components prevents us from reducing the power radiated by the box, we shall consider in the following part that the consumption of the access point does not change between the centralized antenna system and the distributed antenna system.

B. Electrical power consumed in Optical chain

The RoF link leads to higher intrinsic power consumption, as a result of the powering/bias needed for such optoelectronic components as the laser emitter and the photodiode. At this stage, recent publications on optically powered remote units for RoF systems enable us to evaluate the (opto-)electrical power consumed in bidirectional RoF links. In [7], a 300m RoF link over multimode fiber was implemented, resulting in an amplified and radiated RF power of 8 dBm. The power consumed by the different devices is reported in Table III. The total power consumed by a single bidirectional RoF link is 174 mW, leading to an overall consumption of 696 mW when four distributed antennas are considered.

TABLE IV: Comparison of energy efficiency, coverage and RF exposition in the two architectures

Criteria	Centralized Antenna	RoF DAS
Total radiated power	17 dBm	14 dBm
Mean throughput reachable	23.8 Mbit/s	37.4 Mbit/s
Mean goodput	9.38 Mbit/s	14.4 Mbit/s
Mean EBG	1.35 J/Mbit	0.357 J/Mbit
Max electrical field received	1.20 V/m	0.427 V/m
Mean electrical field received	$1.42\ 10^{-3}$ V/m	$2.95\ 10^{-3}$ V/m

C. EBG comparison for different architectures

From the electrical power consumption model of the RoF link, the total EBG in the whole architecture can be computed, assuming that the optical power does not change with the modulation scheme.

$$\text{EBG (J/Mbit)} = \frac{P_{AP} + P_{dgl} + P_{opt} \text{ (W)}}{D \text{ (Mbit/s)}} \tag{4}$$

The EBG values obtained are reported in Figure 2. Table IV shows different parameters obtained from our simulations to compare performance, coverage, energy efficiency and radio frequency exposure in centralized antenna system and in RoF DAS. The mean throughput, goodput and EBG are computed considering the area where a connection is possible in the first configuration, i.e. 92.3% of the total area.

The mean EBG in our centralized antenna system is 1.35 J/Mbit, this value decreasing to 0.357 J/Mbit for four RoF distributed antennas over the same area. Despite additional consumption by optical devices, the energy efficiency is 3.79 times better in RoF DAS than with the centralized antenna system, all the more since the total radiated power is divided by two in the former case. Considering isotropic antennas and the impedance of vacuum, the mean and the maximum strengths of the electrical field received in our area are computed in Table IV. When users are close to the emitter in the centralized antenna system, the maximum strength of the electrical field is three times higher than in the RoF DAS. However, the mean strength of the electrical field is twice as high in the RoF DAS case, due to the number of antennas used. Full control of the optical components via the MAC layer [8] may allow us to restrict the RF transmission to only those cells where communication is required by a mobile terminal. As an example, if the previous simulation is performed with only one distributed antenna that emits 8 dBm, the mean strength of the electrical field decreases down to $3.1\ 10^{-4}$ V/m, with the same transmission performance.

V. Conclusion

This paper shows the advantages of a distributed antenna network in terms of energy efficiency coverage and radiofrequency exposure. Commercial device datasheets are used to link up the RF power received by a terminal with the 802.11 modulation scheme. The instantaneous power consumption of a Wi-Fi access point and USB Dongle are measured for different modulation schemes to evaluate the energy-per-bit goodput as a function of the distance between the access point and a dongle. Simulations show that a distributed system with four antennas is 3.8 times more energy-efficient than a centralized antenna system, while the total radiated power is divided by a factor of two. However, it could be interesting to investigate the influence of the environment topography (e.g., the power decay index n) on the energy efficiency. Moreover, the number of remote antennas and the corresponding radiated power have to be investigated with the knowledge of a topography.

Additional improvement in energy efficiency and RF exposure of DAS may be expected thanks to full control of the optical components via the MAC layer [8]. With this kind of architecture, the RF power is only radiated on the spot(s) where and when some communications are required in the presence of mobile terminals. Further increase in energy efficiency can be achieved by switching off the access point and wake it up in the absence of communication request in the area [9]. Finally, even if RoF DAS have better performance in terms of coverage and energy efficiency, the ultimate objective would be to evaluate the impacts on the overall carbon footprint of the additional (optical) components added in the network. This point is currently being studied and will be shortly submitted for publication.

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